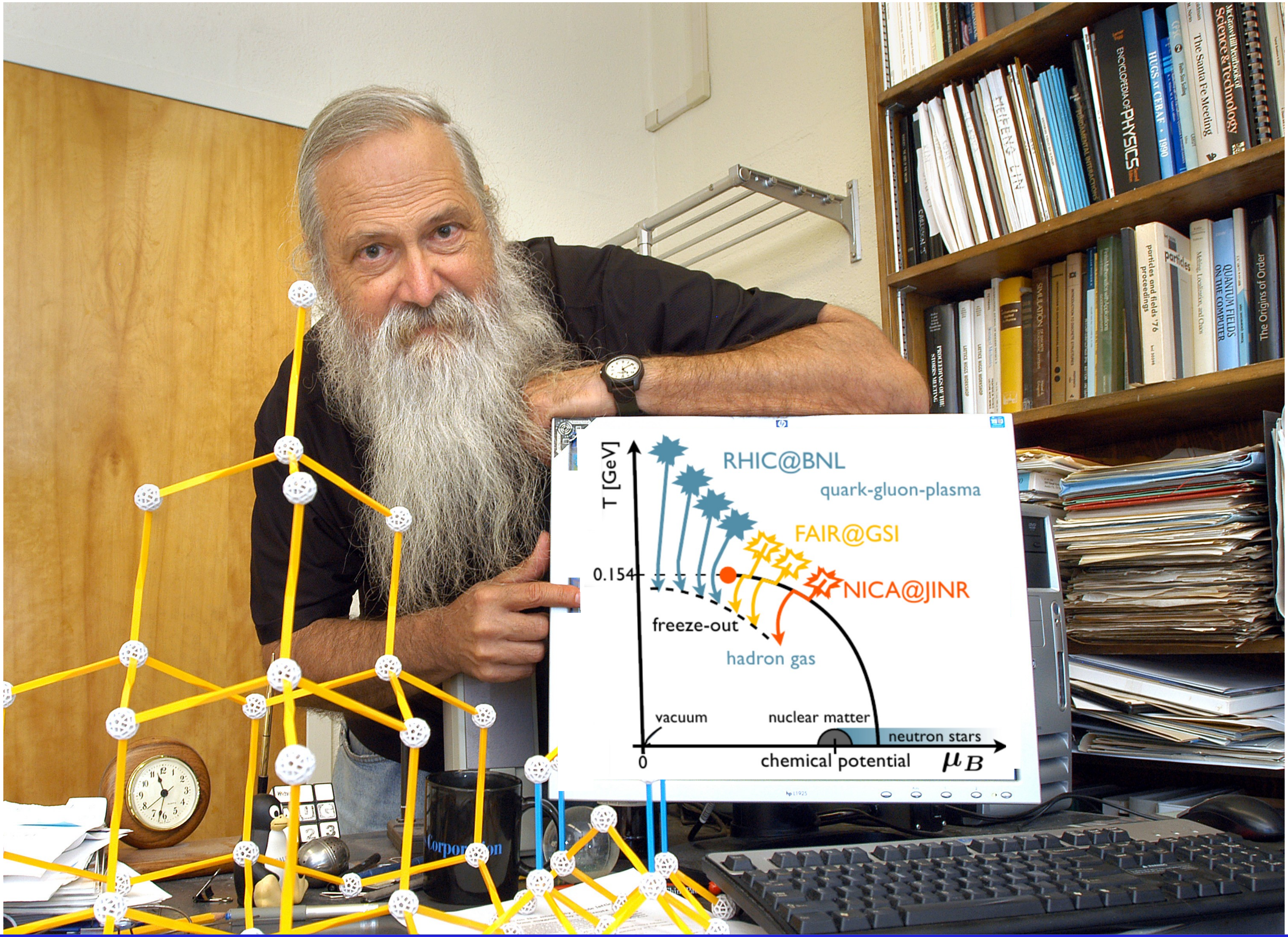
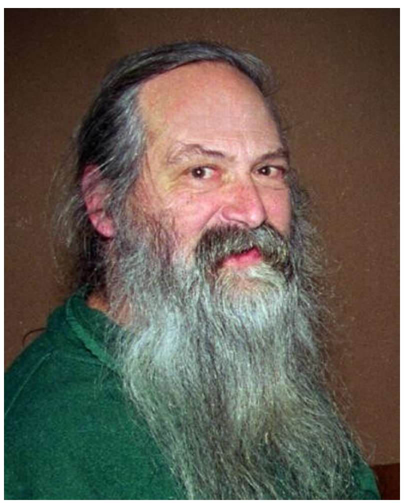
Conserved charge fluctuations and the phase diagram of strongly interacting matter

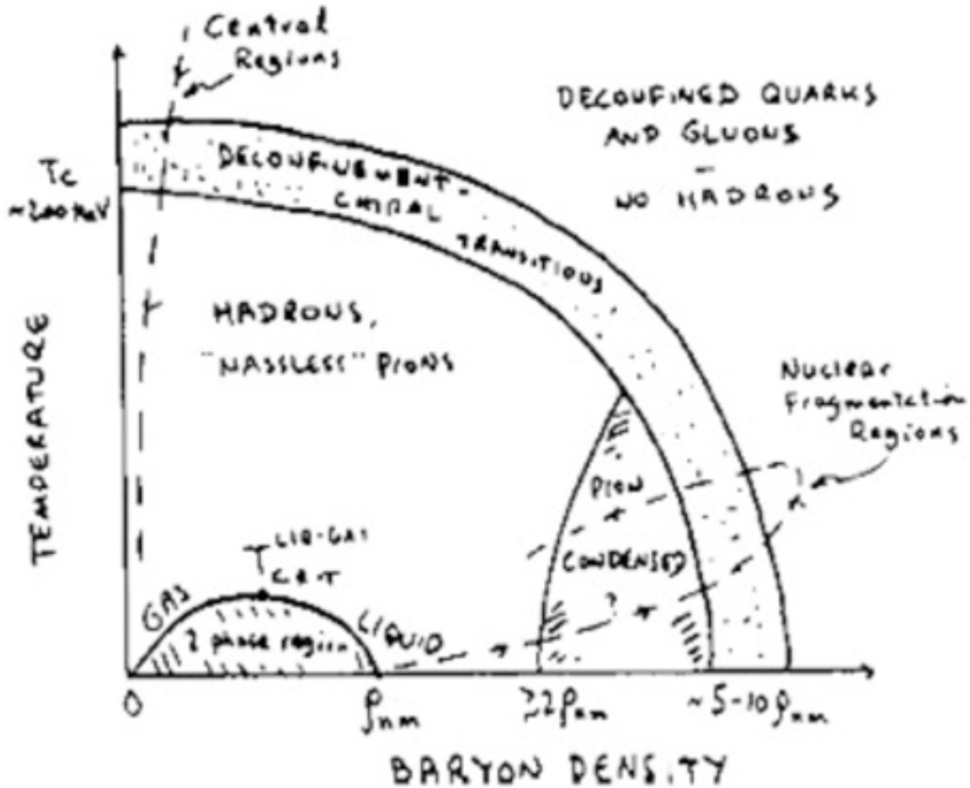
Frithjof Karsch, BNL/Bielefeld



Strongly interacting matter in the '70s



Mike Creutz



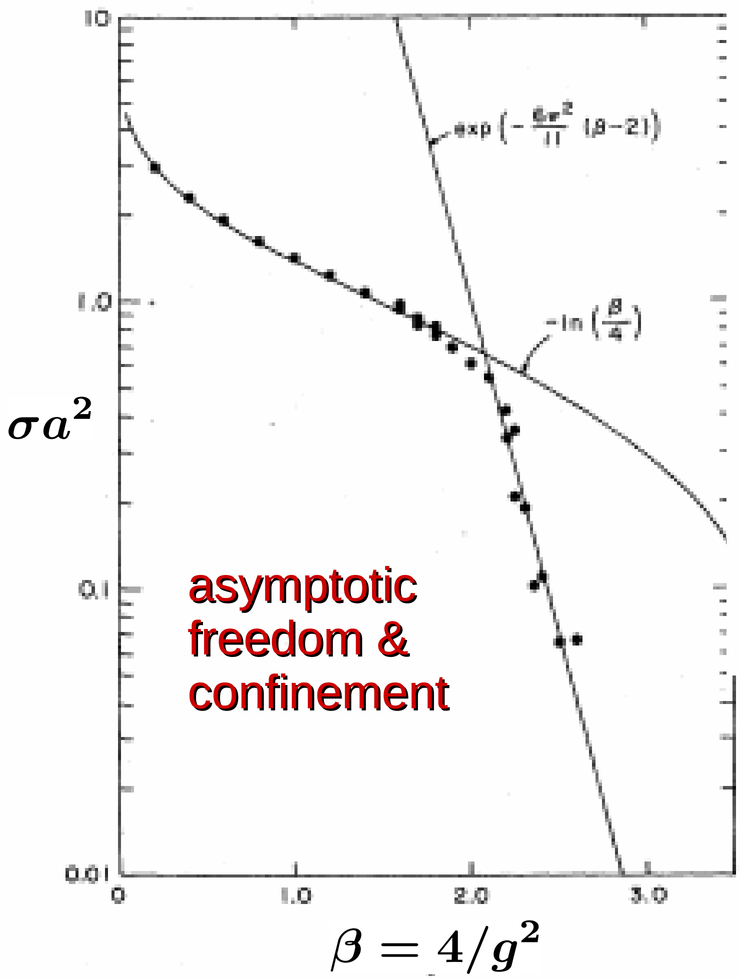
Gordon Baym: Long Range Plan 1983

Rolf Hagedorn:
Hadron resonance gas,
ultimate temperature?

– the physics/thermodynamics of strong interaction matter is described by the theory of strong interactions – Quantum Chromo Dynamics (QCD)

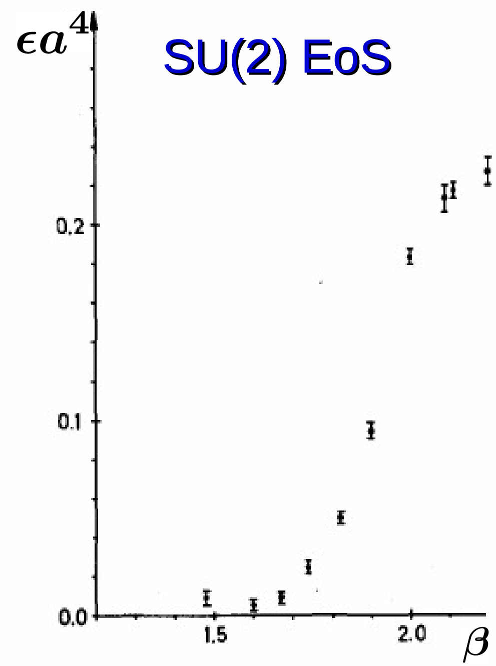
– understanding highly non-perturbative/collective effects like phase transitions requires the application of numerical techniques – lattice QCD

Asymptotic Freedom
Equation of state and Hadron Resonance Gas

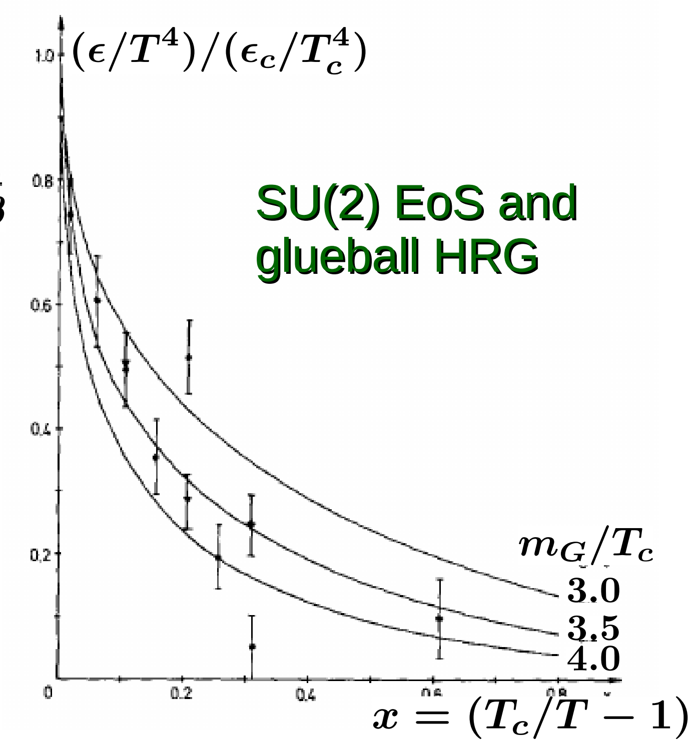


M. Creutz,
Phys. Rev. D21 (1980) 2308

Volume 101B, number 1,2 PHYSICS LETTERS 30 April 1981



J. Engels et al.,
PL 101B (1981)



J. Engels et al.,
PL 102B (1981)

QCD-EoS and the Hadron Resonance Gas (HRG)

HRG thermodynamics

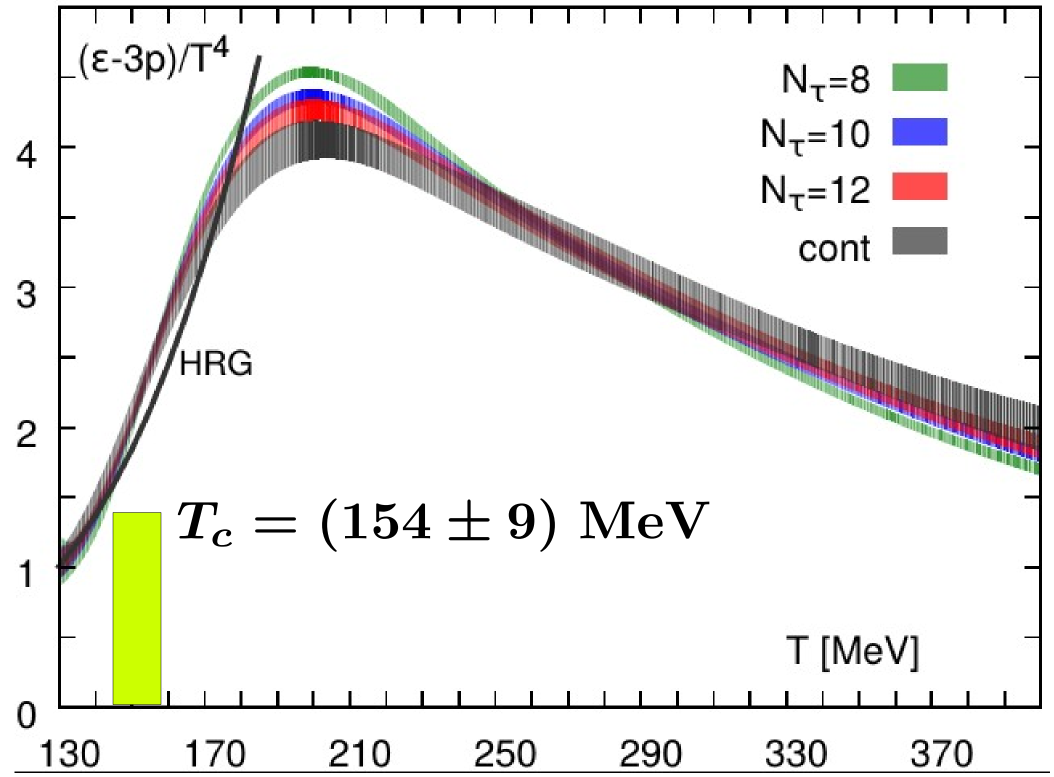
Pressure
$$\frac{P}{T^4} = \sum_{m \in mesons} \ln Z_m^b(T,V,\mu) + \sum_{m \in baryons} \ln Z_m^f(T,V,\mu)$$

Trace anomaly
$$\frac{\epsilon - 3P}{T^4} = T \frac{\mathrm{d}P/T^4}{\mathrm{d}T}$$

$$\left(\frac{\epsilon - 3P}{T^4}\right)_{\mathrm{QCD}} > \left(\frac{\epsilon - 3P}{T^4}\right)_{\mathrm{HRG}}$$

larger pressure, larger trace anomaly

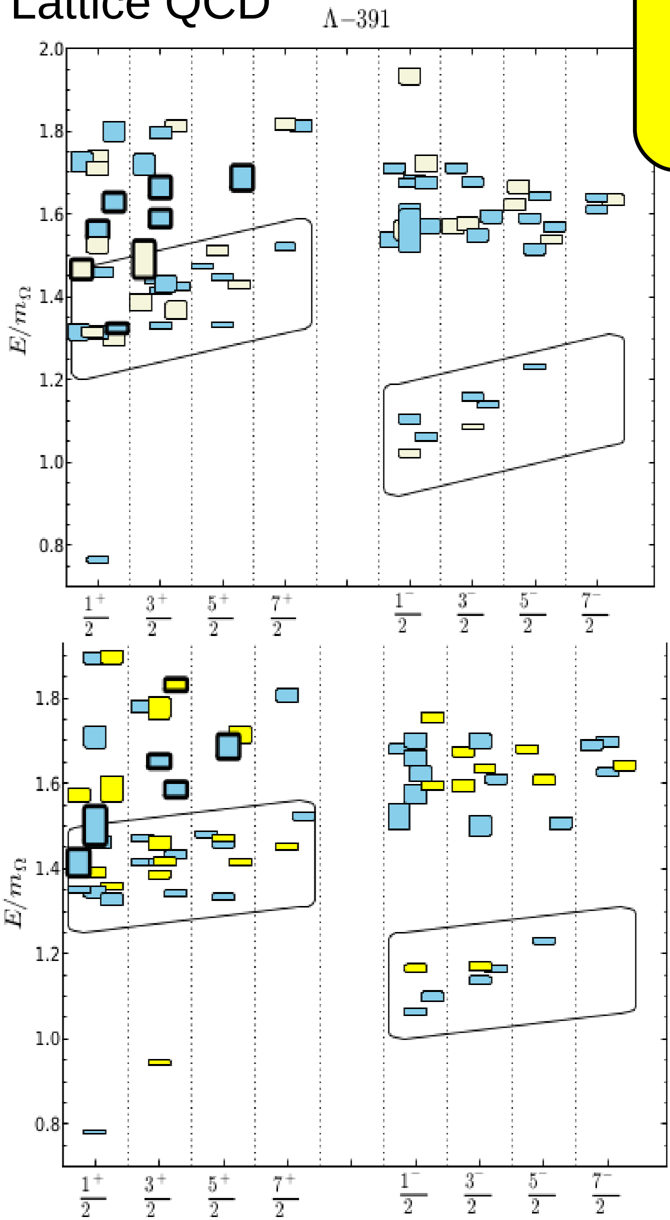
there is 'room for additional resonances' not accounted for by the HRG model



hotQCD , arXiv:1407.6387

Probing the hadron spectrum using QCD thermodynamics

Lattice QCD



$$P_{tot} = \sum P_h$$

h=all hadrons

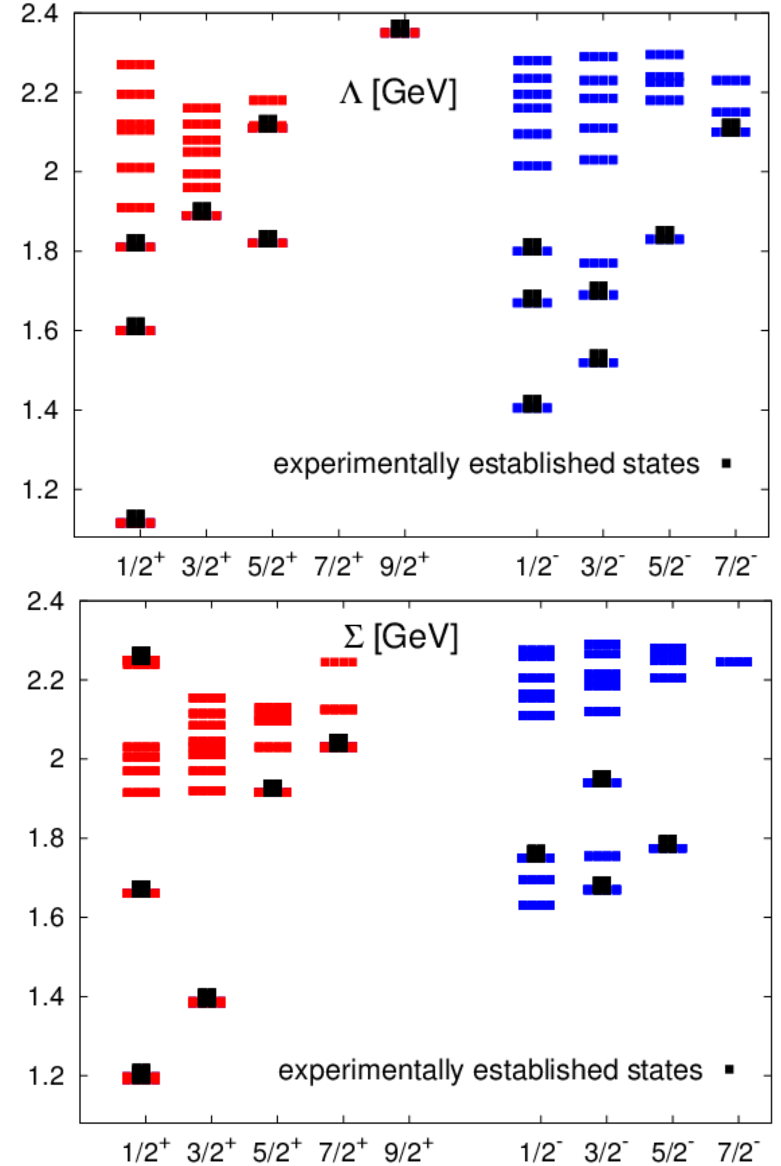
strange baryons

more strangeness

=

larger fluct.

Quark Model



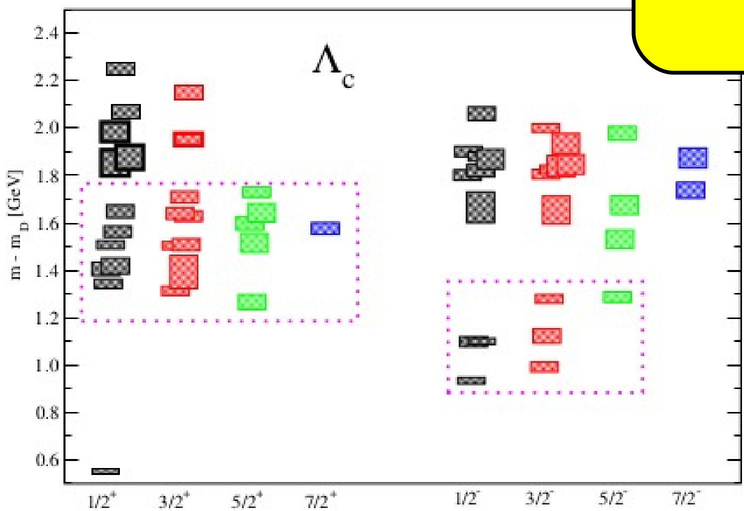
R. Edwards et.al., Phys. Rev D87, 054506 (2013)

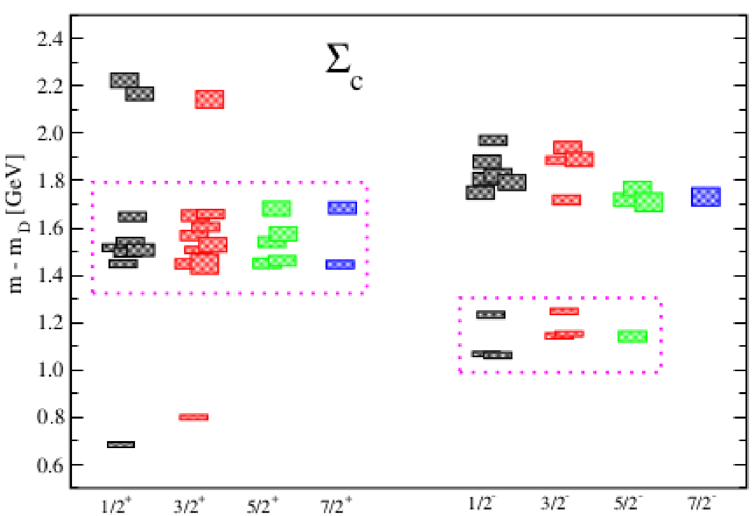
S. Capstick, N. Isgur, Phys. Rev. D34, 2809 (1986)

Probing the hadron spectrum using QCD thermodynamics

$$P_{tot} = \sum_{\text{h=all hadrons}} P_h$$

Lattice QCD





M. Padmanath et.al., arXiv:1311.4806

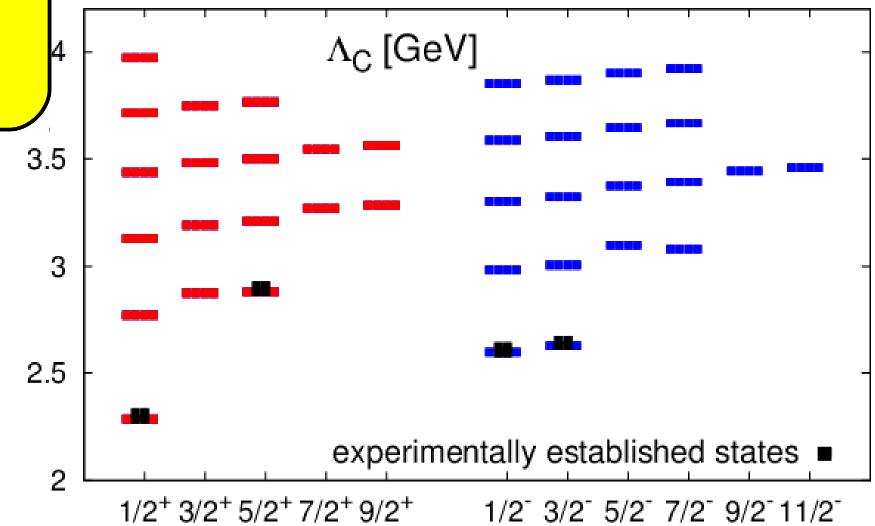
charmed baryons

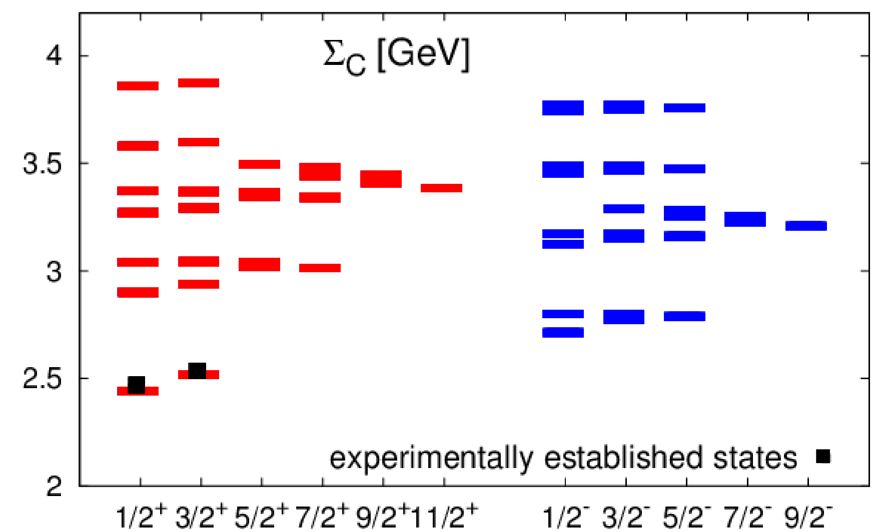
more charm

=

larger fluct.

Quark Model





D. Ebert et. al., Eur. Phys. J. C66, 197 (2010); Phys. Rev. D84, 014025 (2011)

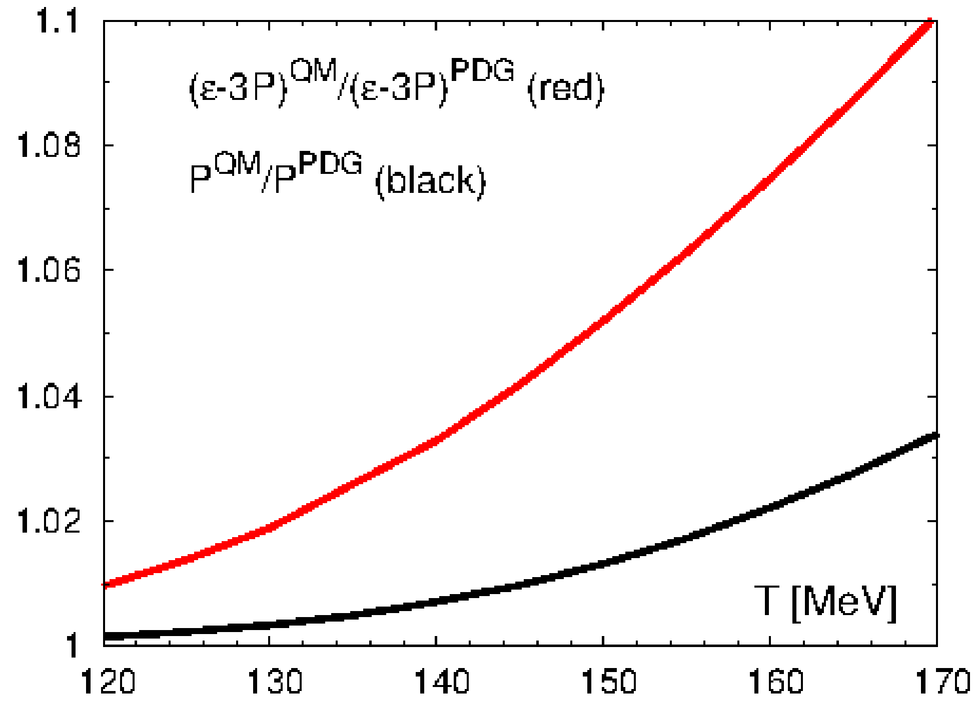
Probing the hadron spectrum using QCD thermodynamics

– additional resonance in the hadron spectrum increase the pressure, energy density as well as trace anomaly

– charmed baryons are too heavy to have any impact on bulk thermodynamics

– additional strange baryons may increase the pressure by about 3% at T=160 MeV

– need to be more selective to see effects of additional strange and charmed hadronic resonances



Fluctuations and Correlations: Susceptibilities

– probing the response of a thermal medium to an external field, i.e. variation of one of its external control parameters: $T,\ \mu,\ m_q$

(generalized) response functions == (generalized) susceptibilities

pressure: $$\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z(V, T, \mu_{B,Q,S}, m_{u,d,s})$$

net number density

$$\chi_1^q = \frac{1}{VT^3} \frac{\partial \ln Z}{\partial \mu_q / T}$$

mean

(quark) number susceptibility

$$\chi_2^q = \frac{1}{VT^3} \frac{\partial^2 \ln Z}{\partial (\mu_q / T)^2}$$

variance

4th order cumulant

$$\chi_4^q = \frac{1}{VT^3} \frac{\partial^4 \ln Z}{\partial (\mu_q / T)^4}$$

kurtosis

generalized quark number susceptibilities:

$$\frac{\partial^{i+j+k} p/T^4}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k}$$

evaluated at

$$\hat{\mu}_X \equiv \mu_X / T = 0$$

Correlations and Fluctuations: HRG vs. LQCD

– construct QCD observables that would project onto specific quantum numbers, if QCD = HRG

E.g.: HRG pressure:

$$\frac{P}{T^4} = \sum_{m \in mesons} \ln Z_m^b(T,V,\mu) + \sum_{m \in baryons} \ln Z_m^f(T,V,\mu)$$

HRG baryon susceptibilities:

$$\chi_{nmkl}^{BQSC} = \sum_{m \in baryons} \left. \frac{\partial^{(n+m+k+l)} \ln Z_m^f(T,V,\mu)}{\partial \hat{\mu}_B^n \partial \hat{\mu}_Q^m \partial \hat{\mu}_S^k \partial \hat{\mu}_C^l} \right|_{\mu=0}$$

sum "knows" about spectrum

Correlations and Fluctuations: HRG vs. LQCD

– in a HRG charge fluctuations obey some simple relations because B, Q, S quantum numbers are integer; –- or even restricted to |B|=0, 1

– baryonic part of the pressure:

$$\frac{P^{baryon}}{T^4} = \sum_{m\in baryons} f(T,m)\cosh(B\mu_B + S\mu_S + Q\mu_Q)$$

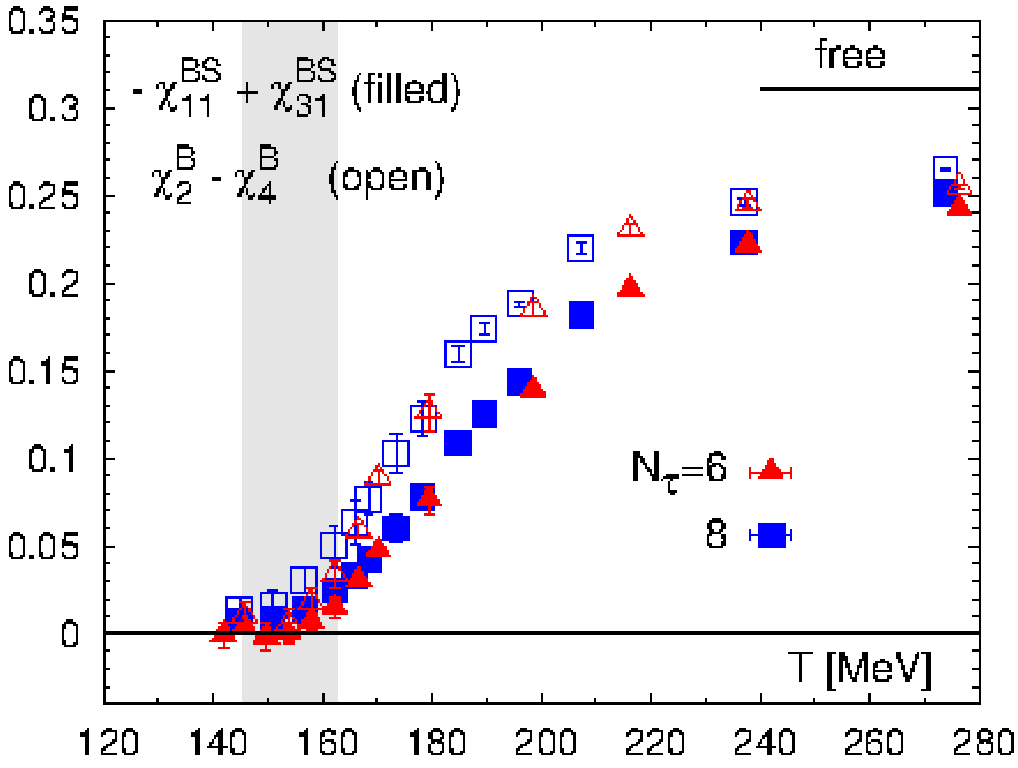
$$\chi_{nmkl}^{BQSC} = \sum_{m\in baryons} \left.\frac{\partial^{(n+m+k+l)} \ln Z_m^f(T,V,\mu)}{\partial\hat{\mu}_B^n \partial\hat{\mu}_Q^m \partial\hat{\mu}_S^k \partial\hat{\mu}_C^l}\right|_{\mu=0}$$

↓

$$\chi_{amkl}^{BQSC} = \chi_{bmkl}^{BQSC} \;, \; a>0,\; b>0, a+b \text{ even}$$

e.g. $\chi_{11}^{BS} = \chi_{31}^{BS}\;,\;\chi_2^B = \chi_4^B \;....$ valid in any HRG (irresp. of the spectrum)

Correlations and Fluctuations: HRG vs. LQCD



– HRG model description of fluctuations and correlations breaks down above T=160 MeV

– this also is the case for the strange baryon sector

A. Bazavov et al. (BNL-Bielefeld-CCNU), Phys. Rev. Lett. 111, 082301 (2013)

Evidence for many charmed baryons in thermodynamics

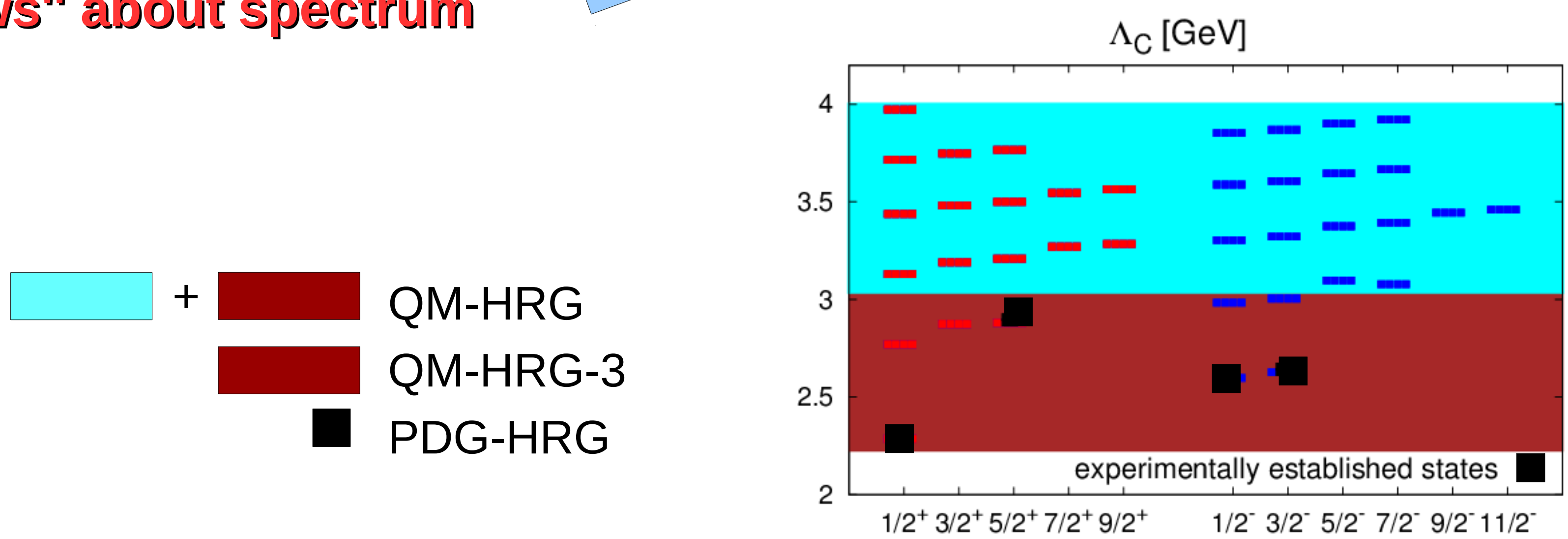
– use charge fluctuations and correlations to probe the hadron spectrum

– HRG pressure of open charmed mesons and baryons particularly simple, because multiple charmed baryons are too heavy to be of thermodynamic relevance; e.g.

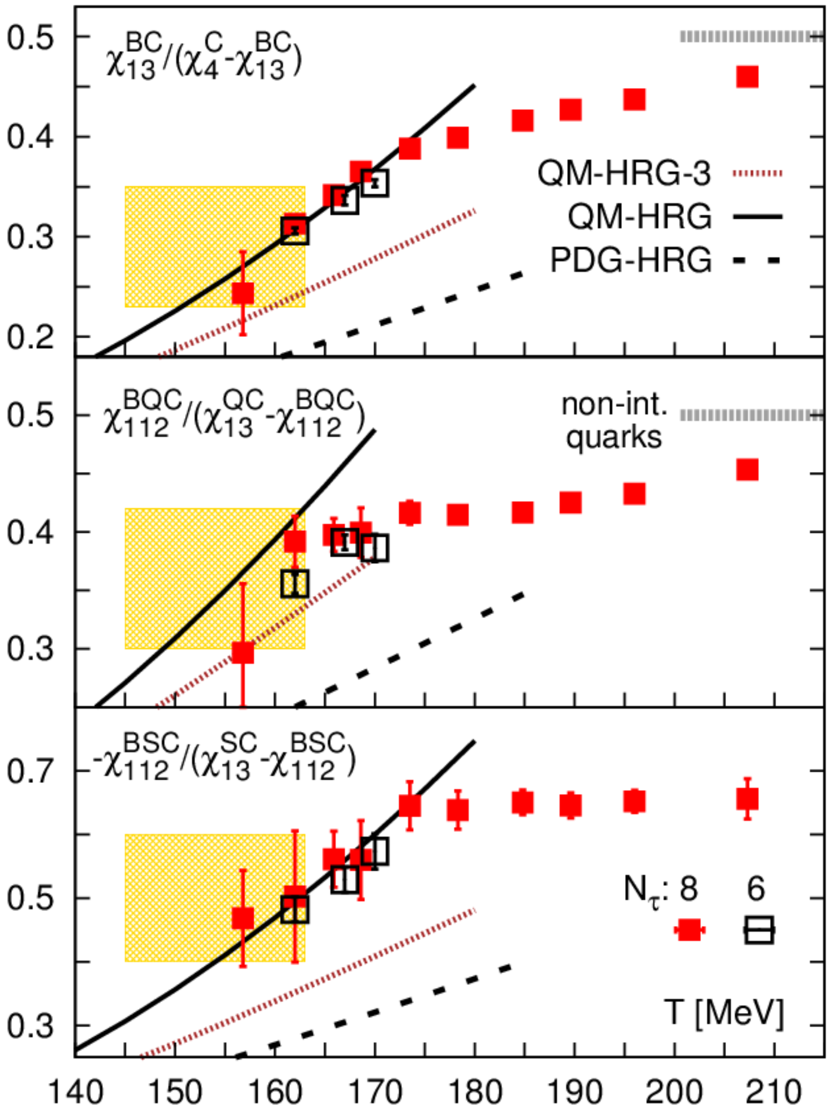
$$\chi_{11}^{BC} \simeq \chi_{22}^{BC} \simeq \chi_{13}^{BC}$$

open charm baryon to meson pressure ratio: $$\frac{B_C}{M_C} = \frac{\chi_{13}^{BC}}{\chi_4^C - \chi_{13}^{BC}}$$

sum "knows" about spectrum



Evidence for many charmed baryons in thermodynamics



A. Bazavov et al., arXiv:1404.4043

close to Tc charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG)

charmed pressure ratios

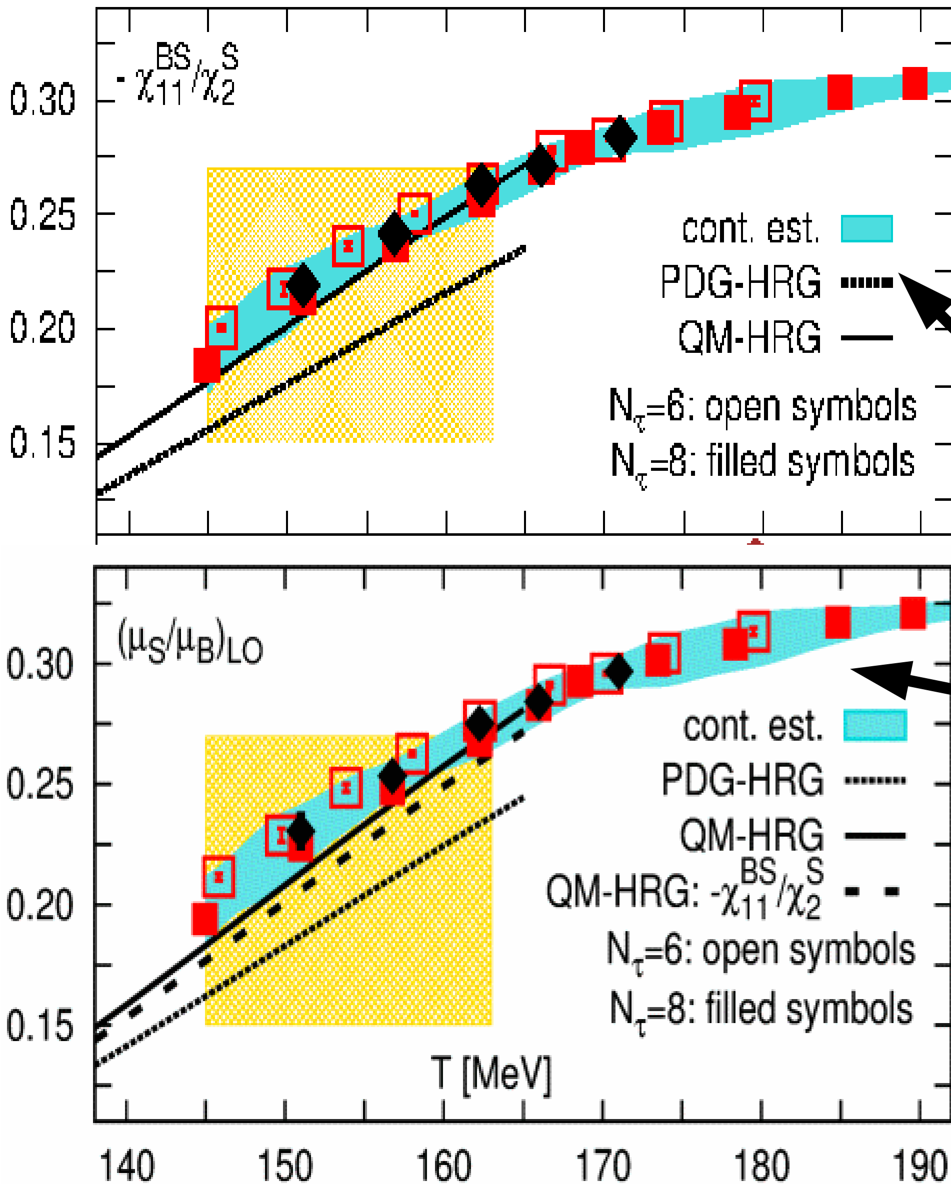
all charmed baryons/mesons

charged charmed baryons/mesons

strange charmed baryons/mesons

including resonance predicted in quark model calculations and observed in lattice QCD calculations allows for a HRG model (QM-HRG) description of lattice QCD results on conserved charge fluctuations and correlations

Evidence for more strange baryons in thermodynamics



A. Bazavov et al.,
Phys. Rev. Lett. 113, 072001 (2014), arXiv:1404.6511

close to Tc strange baryon fluctuations are about (10-20)% larger than expected in a HRG based on known strange baryon resonances (PDG-HRG)

QM-HRG model agrees well with lattice QCD

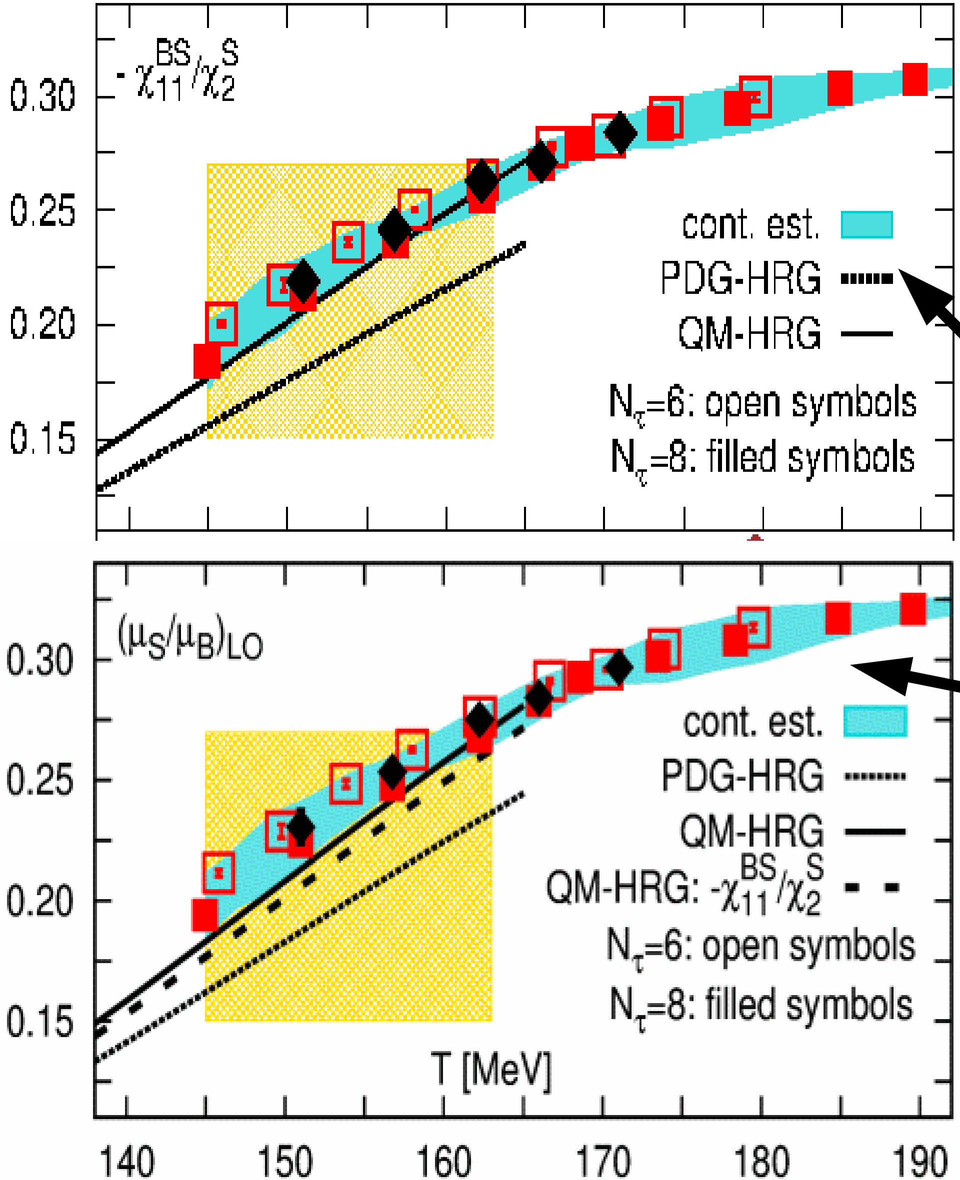
enhanced
strangeness-baryon correlation over strangeness fluctuations

strangeness neutrality
enforces relation between chemical potentials

$$\langle n_S \rangle = 0$$
$$= \chi_2^S \hat{\mu}_S^2 + \chi_{11}^{BS} \hat{\mu}_S \hat{\mu}_B + \mathcal{O}(\mu^4)$$

$$\frac{\mu_S}{\mu_B} = -\frac{\chi_{11}^{BS}}{\chi_2^S} + \mathcal{O}(\mu^2)$$

Evidence for more **strange baryons** in thermodynamics



A. Bazavov et al.,
Phys. Rev. Lett. 113, 072001 (2014), arXiv:1404.6511

close to Tc strange baryon fluctuations are about (10-20)% larger than expected in a HRG based on known strange baryon resonances (PDG-HRG)

QM-HRG model agrees well with lattice QCD

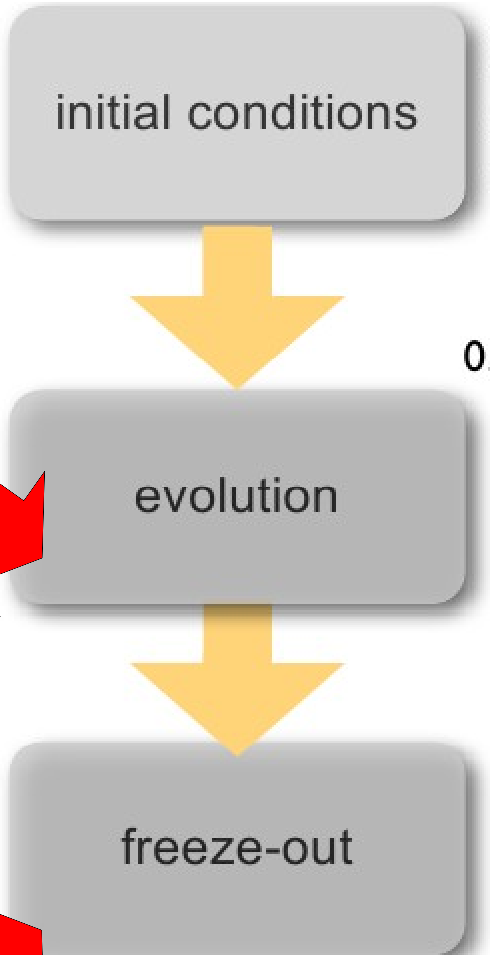
enhanced
strangeness-baryon correlation over strangeness fluctuations

enhanced
strangeness over baryon chemical potential ratio

leads to the prediction of a
smaller freeze-out temperature

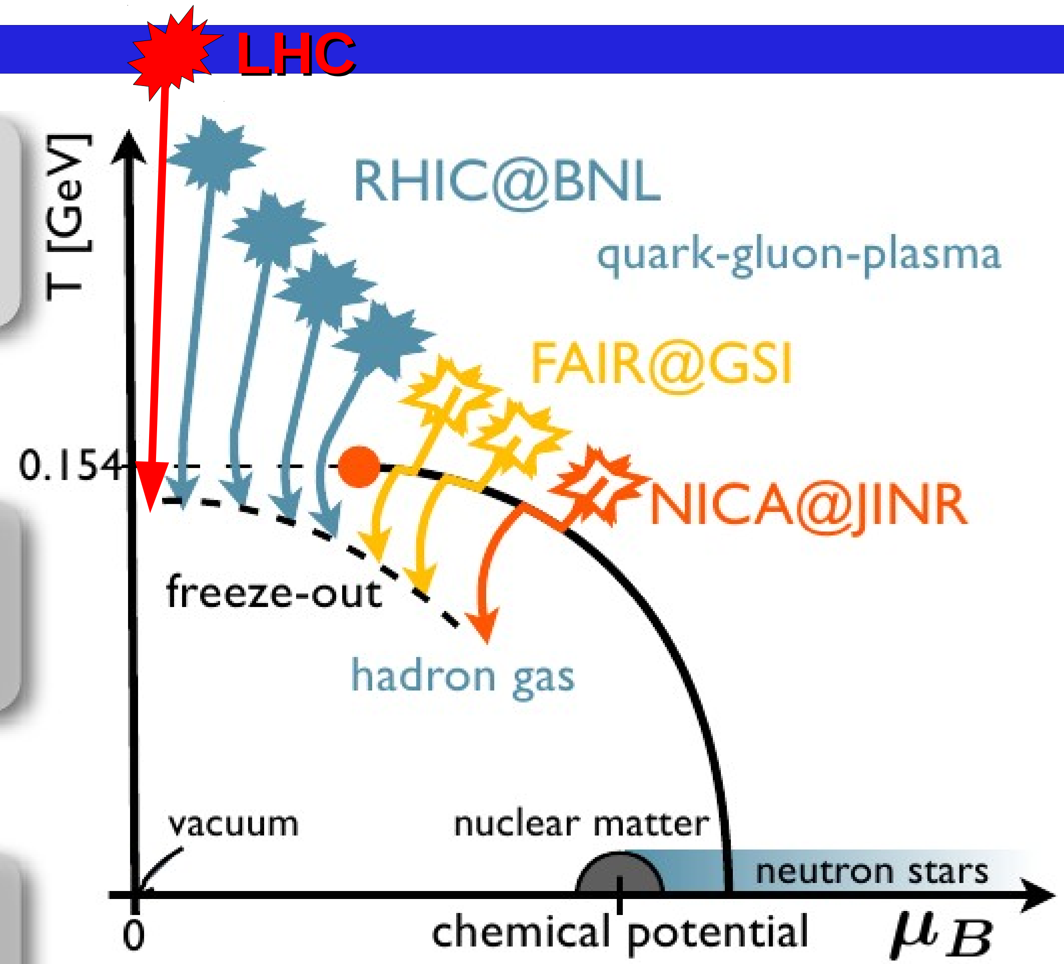
Exploring the QCD phase diagram

controlled by the **QCD equation of state**, T_c



expectation:
freeze-out close to QCD transition line

observable consequences:
freeze-out/hadronization pattern of mesons and baryons, controlled by T_f, μ_B, μ_S



– LHC: establish contact with the QCD PHASE transition

– RHIC: locate/provide evidence for the QCD critical point

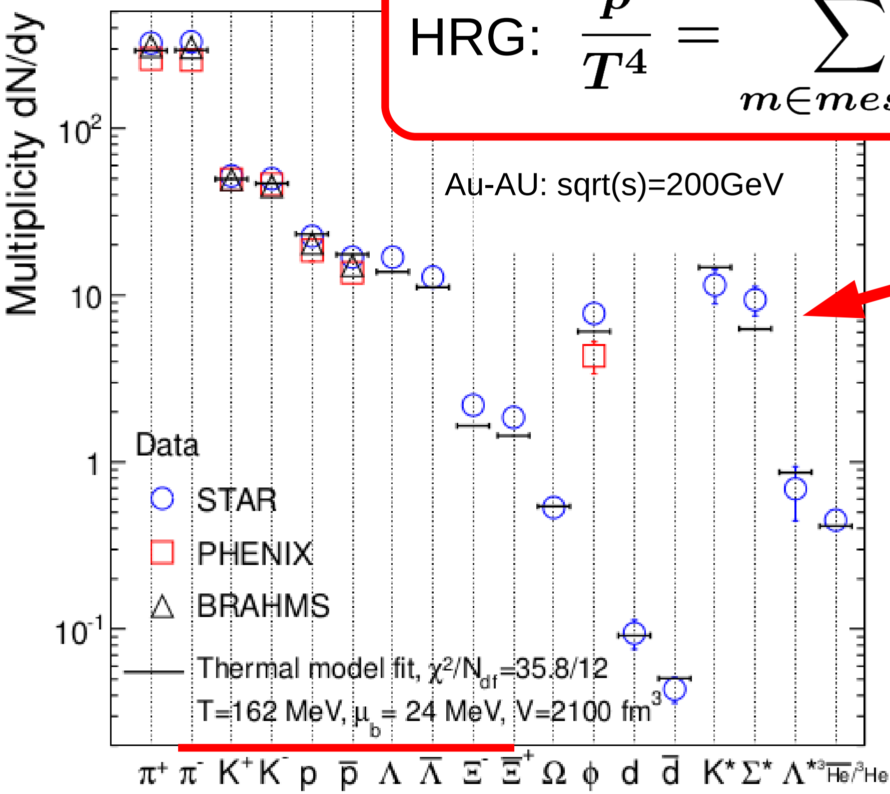
HRG model, lattice QCD and critical behavior

- **for a wide range of baryon chemical potentials freeze-out happens in or close to the QCD transition region:** predicted ➡ P. Braun-Munzinger et al., Phys. Lett. B596, 61 (2004)

caveat: freeze-out parameter extracted from experimental data by comparing to the Hadron Resonance Gas (HRG) model, i.e. not QCD

HRG: $$\frac{p}{T^4} = \sum_{m \in meson} \ln Z_m^b(T,V,\mu) + \sum_{m \in baryon} \ln Z_m^f(T,V,\mu)$$

$$\sim e^{-m_H/T} e^{(B\mu_B + S\mu_S + Q\mu_Q)/T}$$



Andornic et.al.: Nucl. Phys. A904, 535c (2013)

goal: describe freeze-out in terms of QCD thermodynamics

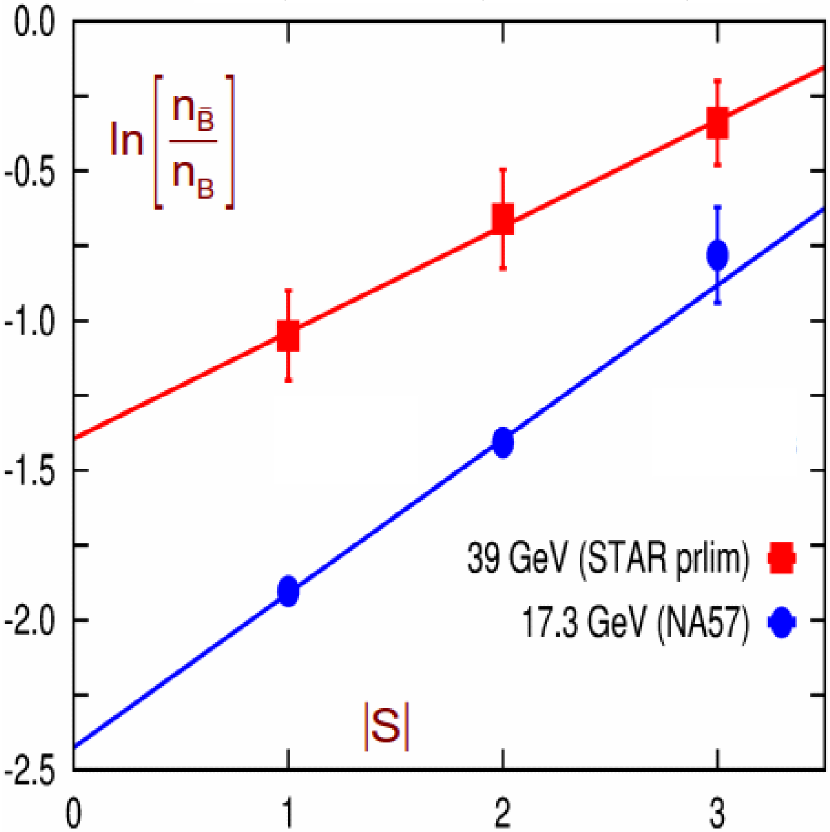
➡ freeze-out parameter from comparison of measured moments of charge fluct. with QCD calculation

BNL-Bielefeld, PRL 109, 12302 (2012)

Strange hadron yields in HIC

$$\frac{n_{\bar{\Lambda}}}{n_{\Lambda}},\ \frac{n_{\bar{\Sigma}}}{n_{\Sigma}},\ \frac{n_{\bar{\Omega}}}{n_{\Omega}} = \exp\left[-\frac{2\mu_B^f}{T^f} - \frac{2\mu_S^f}{T^f}|S|\right] = \exp\left[-\frac{2\mu_B^f}{T^f}\left(1-\frac{\mu_S^f}{\mu_B^f}|S|\right)\right]$$

$\Lambda/\bar{\Lambda}$ $\Sigma/\bar{\Sigma}$ $\Omega/\bar{\Omega}$



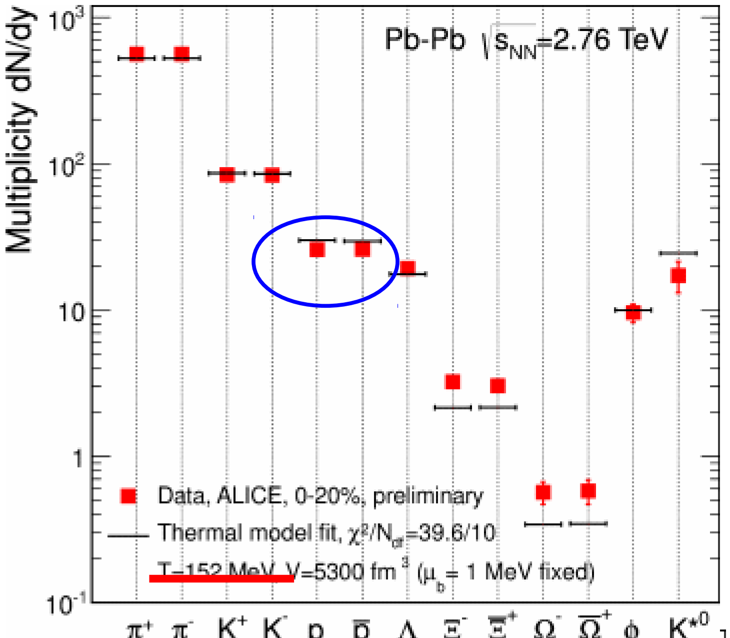
presence of unobserved higher resonances get imprinted in the yields of ground state hadrons

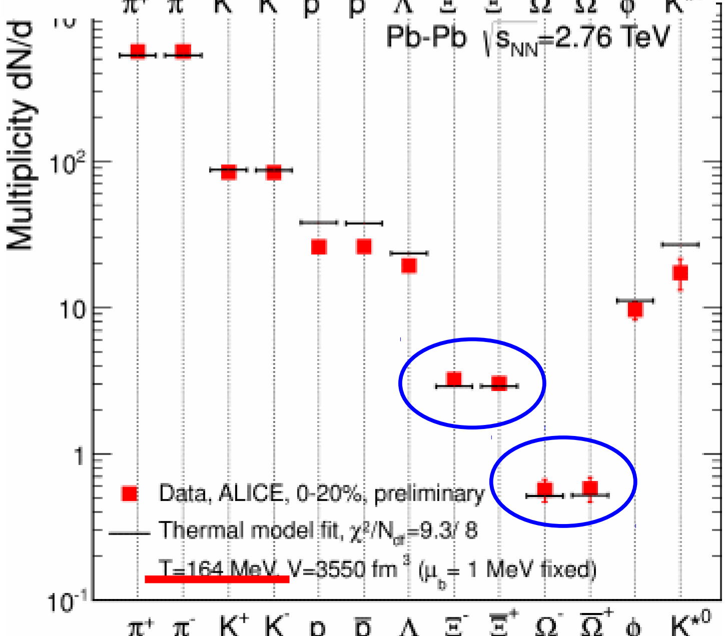
extract chemical potentials from particle/anti-particle ratios of multiple strange baryon yields (eliminates mass dependence)

data:

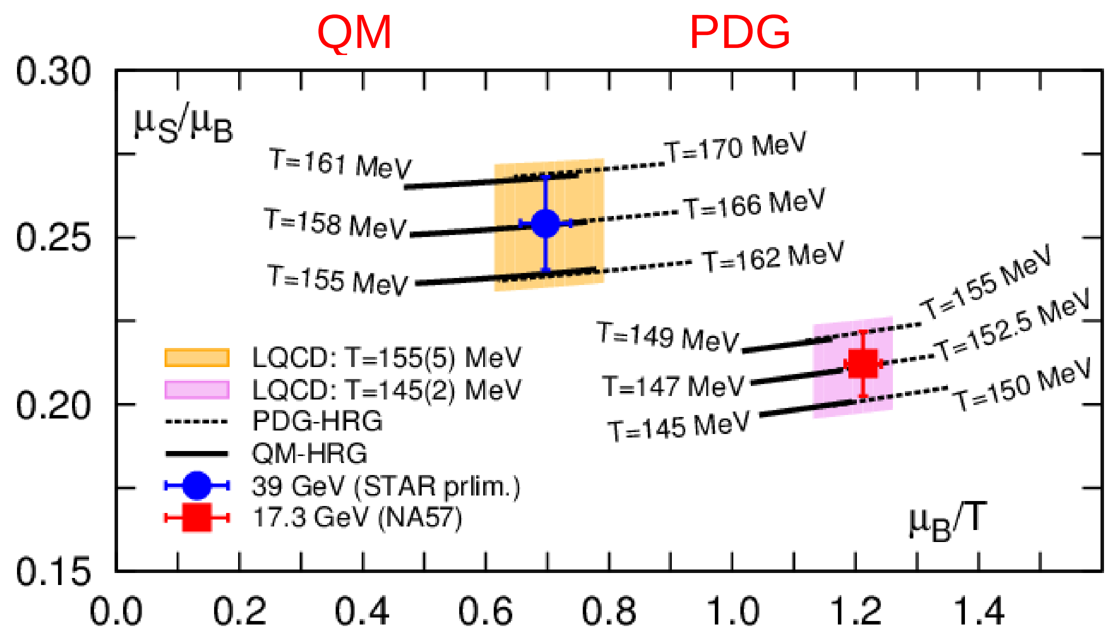
STAR: F. Zhao, PoS CPOD2013 (2013) 036
NA57: F. Antinori et al, PLB 595 (2004) 68

Impact on determination of freeze-out parameter





A. Andronic et.al.: Nucl. Phys. A904, 535c (2013)



A. Bazavov et al., Phys. Rev. Lett. 113, 072001 (2014), arXiv:1404.6511

including more strange baryons will change determination of freeze-out parameters

better agreement of strange and non-strange particle yields at lower freeze-out temperature

Conclusions

- Thanks to Mike's pioneering work

  LGT calculations have achieved two important goals of studies of strong interaction thermodynamics

  – determination of transition temperature Tc
  – calculation of the equation of state

  with physical quark masses in the continuum limit

- Gross features of bulk thermodynamics at low temperatures are compatible with hadron resonance gas thermodynamics;

- deviations from PDG-HRG provide

  evidence for a richer strange and charmed baryon spectrum than so-far known experimentally